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MIXING COEFFICIENT FOR ICE-COVERED FLOWS

by

Y.L. Lau

Environmental Hydraulics Section
Hydraulics Division
National Water Research Institute
Canada Centre for Inland Waters
Burlington, Ontario

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ABSTRACT

The procedures and results of mixing tests conducted under ice-covered flows in four river reaches are described. The results are compared with those from open-water tests on the same four reaches.

RESUME

Le présent document décrit le déroulement et les résultats d'essais effectués dans quatre tronçons de cours d'eau englacés afin de vérifier le coefficient de mélange

MANAGEMENT PERSPECTIVE

This paper provides an important piece of information for the computation of the concentrations of dissolved substances as it diffuses across a stream. Calculation of the concentrations depends on knowing the mixing coefficient. This paper shows that if the mixing coefficient is known for open water then it can be correctly deduced for the ice covered condition because $e/(\tau/\rho)^{1/2}$ H is a constant for ice covered and open flow conditions. e is the coefficient, τ is the total shear stress on the flow, ρ is the water density and H is the mean flow depth. This paper converts some previous computations and shows the connection between open-water and frozen conditions. All modellers of water quality should note this.

T. Milne Dick
Chief
Hydraulics Division

PERSPECTIVE DE GESTION

Ce rapport fournit des données importantes pour le calcul des concentrations de substances dissoutes à mesure qu'elles sont diffusées dans un cours d'eau. Pour effectuer ces calculs, il faut connaître le coefficient de mélange. Si le coefficient de mélange dans un cours d'eau libre de glace est connu, il peut être déduit correctement pour un cours d'eau englacé, car $e/(\tau/p)^{1/2}$ H est une constante propre à ces deux situations, e étant le coefficient, τ l'effort de cisaillement total exercé sur l'écoulement, p la densité de l'eau et H la hauteur d'écoulement moyenne. A partir de calculs antérieurs, nous établissons ici un rapport entre les cours d'eau libres de glace et les cours d'eau englacés. Ce rapport devrait donc intéresser tous ceux qui s'occupent de modélisation pour la gestion de la qualité des eaux.

T. Milne Dick
Chef
Division de l'hydraulique

1.0 INTRODUCTION

The calculation of the mixing of pollutants or other tracers in rivers and streams requires knowledge of the value of the mixing coefficient as input to the analytical or numerical models being used. For open water conditions, many measurements of the transverse mixing coefficient have been made, both in the laboratory and in the field. These data have been summarized by Lau and Krishnappan (1981a) who presented a curve for the dimensionless transverse mixing coefficient as a function of the aspect ratio of the stream.

When a stream becomes ice covered, the velocity, shear stress and diffusivity distributions are all changed substantially (Sayre and Song, 1979; Lau and Krishnappan, 1981b). Under such conditions, it is almost expected that the mixing coefficient will be affected. However, there are very few published measurements of the transverse mixing coefficient under ice-covered conditions. Beltaos (1980) reported measurements in three river reaches under ice-covered as well as open-water conditions. Engmann (1974) also made measurements in a river as well as in laboratory flumes. Unfortunately, in Engmann's experiments, the effects of transverse advection were not measured but were lumped together with the dispersion term. Therefore, the values of the mixing coefficient reported by Engmann are not really valid and cannot be compared with values from other investigators. The only exceptions are his data from a straight flume, in which transverse advection did not come into play.

In the straight laboratory flume, Engmann found that the value of the transverse mixing coefficient e_z for flows with top covers were only about half the magnitude of those for the corresponding free surface flows. When non-dimensionalized with the shear velocity U_* and the flow depth H, the dimensionless mixing coefficient e_z/U_*H was about half that of the free-surface flow. Because the hydraulic radius R in a covered flow is about half the value of H, the mixing coefficient e_z/U_*R turned out to be approximately the same as for

the free surface flows. These results are quite different from those of Beltaos who used measurements from the Athabasca and Beaver Rivers in Alberta and found that the values of e_z/U_*H are about the same for ice-covered and free-surface conditions while e_z/U_*R values are larger for ice-covered flows. Therefore, more measurements are required to resolve the difference in these findings as well as to better define the variation of e_z with bulk hydraulic variables.

This report describes the procedures and the results of the field measurements of transverse mixing in four river reaches under ice-covered conditions.

2.0 TEST SITES

Four river reaches in Southern Ontario were selected. Three of these were on the Nith River and one was on the Grand River. Fig. 1 shows the location of these sites. These sites were chosen because field tests of transverse mixing for open-water conditions had been conducted previously at these locations.

3.0 TEST METHOD

In general, the tests consisted of injecting dye at a constant rate into the river through a hole drilled in the ice. Measurements were made at a number of cross sections downstream. At each cross section holes were drilled in the ice at a number of locations across the river. Velocity and depth measurements were made at each hole and water samples were taken for the analysis of dye concentration in the laboratory. These measurements were then used with the model RIVMIX to calculate the transverse mixing coefficient. Further details of the experiments are given below.

4.0 TRACER

Rhodamine B dye was used as the tracer. Prior to each test, 40 litres of 2% solution were prepared. At the injection site, a 20 cm diameter hole was drilled in the ice. A portable heated shelter (Fig. 2) was set up over the hole and the dye solution was delivered into the hole at the rate of 100 ml per minute by means of a peristàllic pump. The solution was actually delivered into a plastic cylinder sitting over the hole and discharged through a nozzle at the base of the cylinder (Fig. 3). The level of the solution in the cylinder allowed any changes in the pumping rate to be detected.

5.0 SAMPLING

Transects where sampling was to be carried out were usually marked out prior to the day of the test. When the field party arrived at a transect, holes would be drilled in the ice at predetermined intervals across the river (Fig. 4). Usually about 20 holes were drilled at each transect. At each hole, the distances from the water surface to the bed and to the underside of the ice were measured using a metering rod with a perforated disk attached to its base. The disk also served as a device for removing slush from the hole. Velocity measurements were made at mid-depth using a miniature Ott meter. Based on the calculations made by Lau for velocity distributions in covered flows (Lau 1982) a correction factor of 0.90 was applied to the velocity readings to obtain the average velocity at that vertical.

Water samples were collected in 125 ml opaque polyethylene bottles. A specially constructed device clamped the bottle in an inverted position while it was being lowered to mid depth. Sample collection was made by turning the bottle to the upright position. The filled bottle was then removed and stored. After sampling had been done at every hole, the field party moved to the next transect downstream and repeated the procedure.

6.0 CONCENTRATION MEASUREMENTS

The dye concentrations were determined with a Turner Model 111 Fluorometer. Calibrations were carried out using solutions of known concentration. A typical calibration curve is shown in Fig. 5. The samples gathered were brought back to the laboratory and were allowed to reach room temperature before concentration measurements were made. Samples were also taken upstream of the injection site to obtain background concentrations. These background values were subtracted from all the other readings.

The value of the tracer flux was calculated for each transect. To account for losses by absorption into the streambed, etc., the concentration readings were normalized to give the same tracer flux as that measured at the first transect.

7.0 CALCULATION OF THE MIXING COEFFICIENT

The mixing coefficients were evaluated by comparing the measured concentrations profiles with those obtained from simulations using the model RIVMIX. The model solves the mass conservation equation using the streamtube concept. Details of the equation and the solution method has been described by Lau and Krishnappan (1981). Therefore, only a brief description is given here.

Simulated concentrations were obtained from numerical solutions of the equation

$$\frac{\partial c}{\partial x} = \frac{1}{Q^2} \frac{\partial}{\partial n} \left[uh^2 m_x e_z \frac{\partial c}{\partial n} \right] \qquad (1)$$

in which x = longitudinal distance coordinate in an orthogonal, curvilinear system; n = dimensionless cumulative discharge, ratio between the cumulative discharge and the total discharge;

c = depth-averaged concentration; Q = total discharge; u = depth-averaged velocity in the x direction; h = local flow depth; m_x = metric coefficient; and e_z = transverse dispersion coefficient.

The measured concentration profile at the first transect was used as input boundary condition and Eq. 1 was solved using a constant value for e_z. The simulated concentration profiles at the various downstream transects were compared with the measured profiles. Different e_z values were tried and the one giving the closest fit was selected as the value for that river reach.

8.0 RESULTS AND DISCUSSION

The simulated and measured concentration distributions are shown in Figs. 6 to 9 for the four test sites. In general, the agreement between simulated and measured concentrations is quite satisfactory. The values of e_z as well as the dimensionless mixing coefficient e_z/U_*H and e_z/U_*R are given in Table 1. Also listed in Table 1 are the hydraulic variables and the corresponding data from the open-water tests. Direct comparison of e_z values are not meaningful because the summer and winter flow rates are different. However it can be seen that for all four sites, the dimensionless mixing coefficient e_z/U_*H are practically the same for open-water and ice-covered conditions. At the same time, e_z/U_*R values are quite different, being almost twice as large for ice-covered conditions. These results agree with the findings of Beltaos (1980) rather than those of Engmann (1974).

In straight, prismatic channels, where the transverse mixing is governed by the diffusive transport resulting from turbulence, one can expect the mixing coefficient to be scaled with the flow depth whether the channel has a free surface or a solid cover. This is because, in either case, the relevant length scale is the distance between the top and bottom boundaries. In natural streams the transverse mixing is not governed by turbulent diffusion alone. The

transport due to differential advection can be just as important, if not more so. However, the present data and those of Beltaos show that the mixing coefficient should still be scaled with the depth rather than with the hydraulic radius.

9.0 CONCLUSIONS

The transverse mixing coefficients evaluated from dispersion experiments in four river reaches showed almost no change in the values of the dimensionless coefficient, e_z/U_*H, between open-water and ice-covered conditions. This agrees with the results obtained by Beltaos from three river reaches in Albeta which have very different characteristics from the rivers studies in this report. These are the only published measurements comparing mixing in natural streams under summer and winter conditions. Therefore, it is recommended that, for calculating mixing in an ice-covered strem, the same value of e_z/U_*H as that for open-water conditions can be used.

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TABLE 1. Reach Average Hydraulic Parameters and Measured Coefficients

Location	Surface Conditions	Width m	Depth m	U m/s	U_* m/s	Sinuosity	e_z m^2/s	$\frac{e_z}{U_* R}$	$\frac{e_z}{U_* H}$
Nith River - Canning	Open Water	36.0	0.54	0.16	0.078	1.25	0.028	0.69	0.66
	Ice Covered	37.5	0.44	0.23	0.051	1.25	0.014	1.26	0.63
Grand River - West Montrose	Open Water	48.0	0.41	0.40	0.070	1.07	0.007	0.25	0.24
	Ice Covered	50.8	0.30	0.34	0.043	1.07	0.003	0.46	0.23
Nith River - Philipsburg	Open Water	15.0	0.48	0.04	0.010	1.30	0.004	0.89	0.83
	Ice Covered	14.6	0.42	0.20	0.007	1.30	0.0025	1.72	0.85
Nith River - Plattsville	Open Water	18.2	0.67	0.17	0.055	1.11	0.020	0.59	0.54
	Ice Covered	18.6	0.55	0.26	0.037	1.11	0.010	0.98	0.49

Fig. 1. Location of Test Sites.

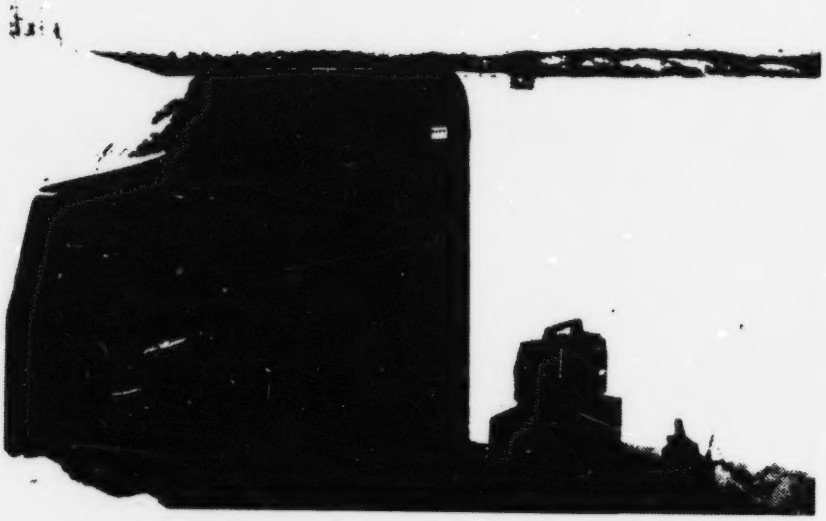

Fig. 2. Shelter for Dye Injection.

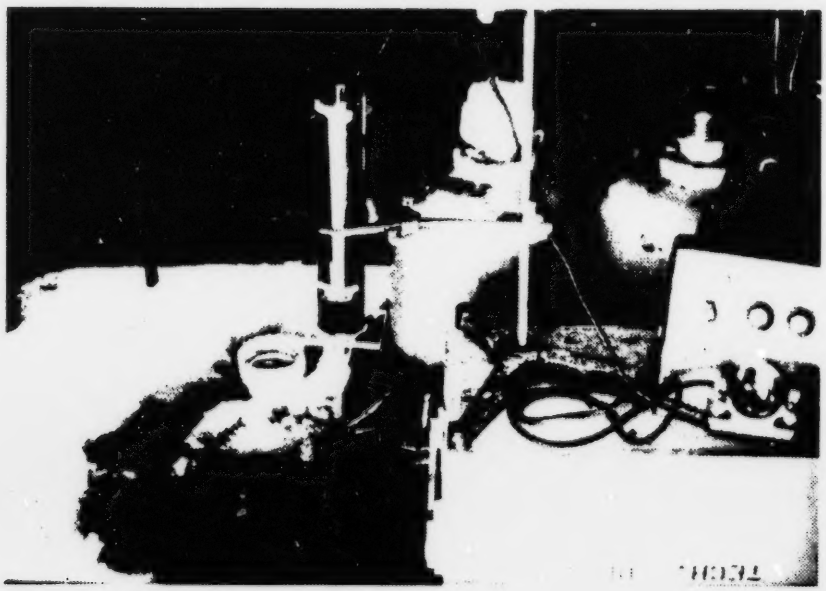

Fig. 3. Injection Apparatus.

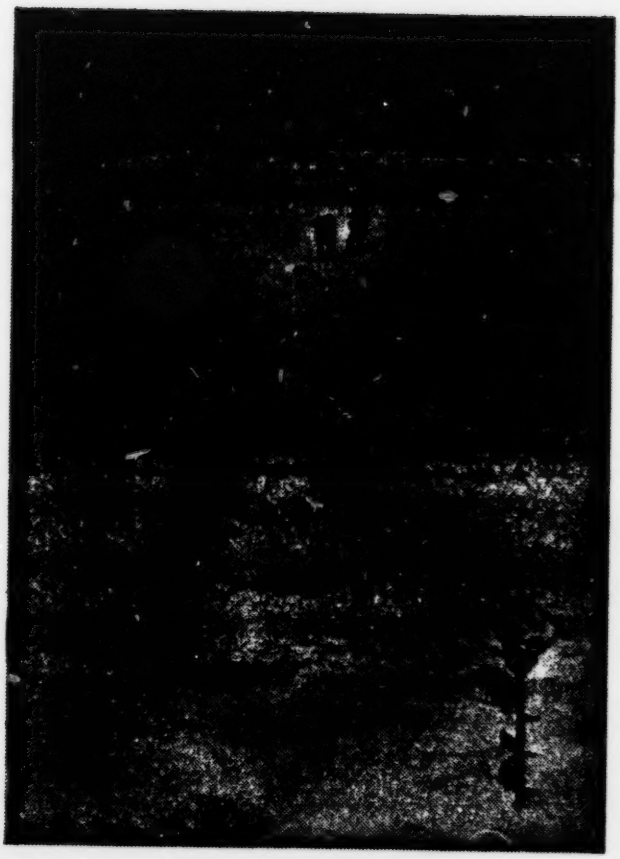

Fig. 4. Holes Drilled for Sampling.

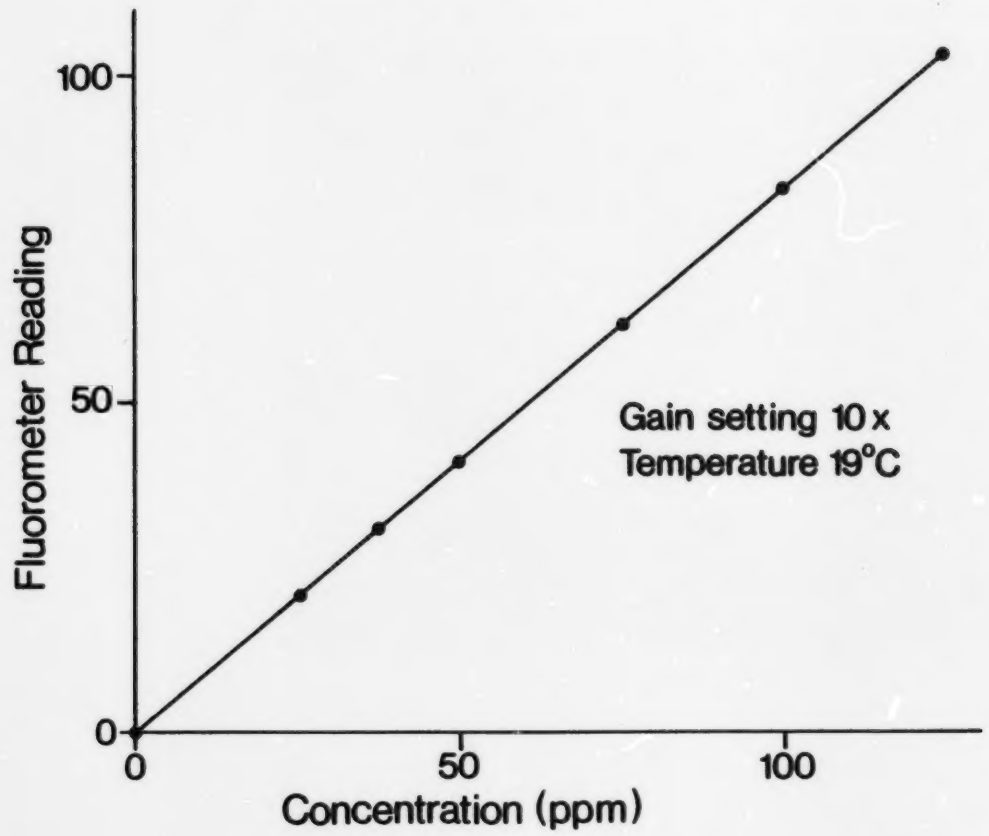

Fig. 5. Typical Calibration Curve for Fluorometer.

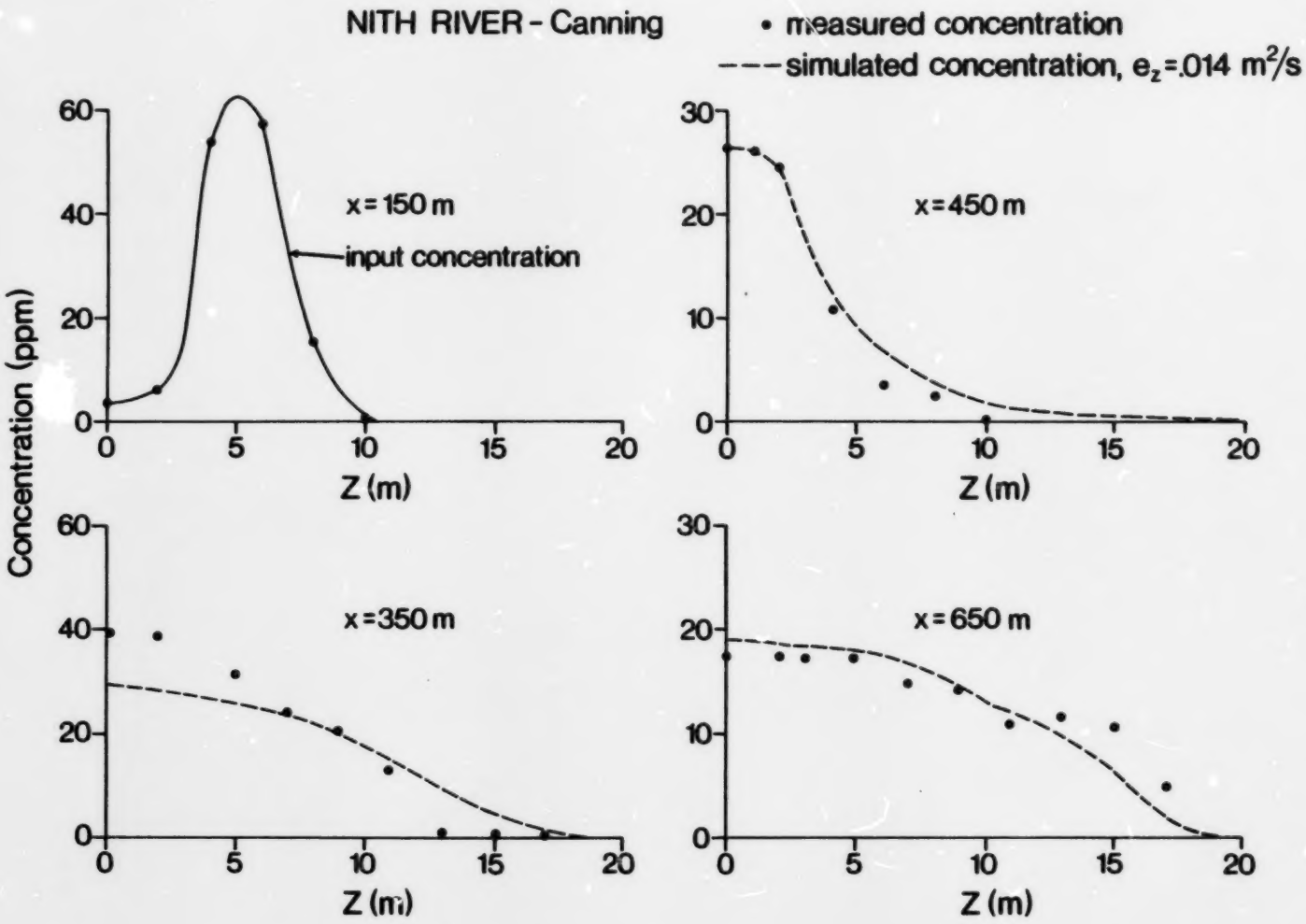

Fig. 6. Simulated and Measured Concentrations - Nith River near Canning.

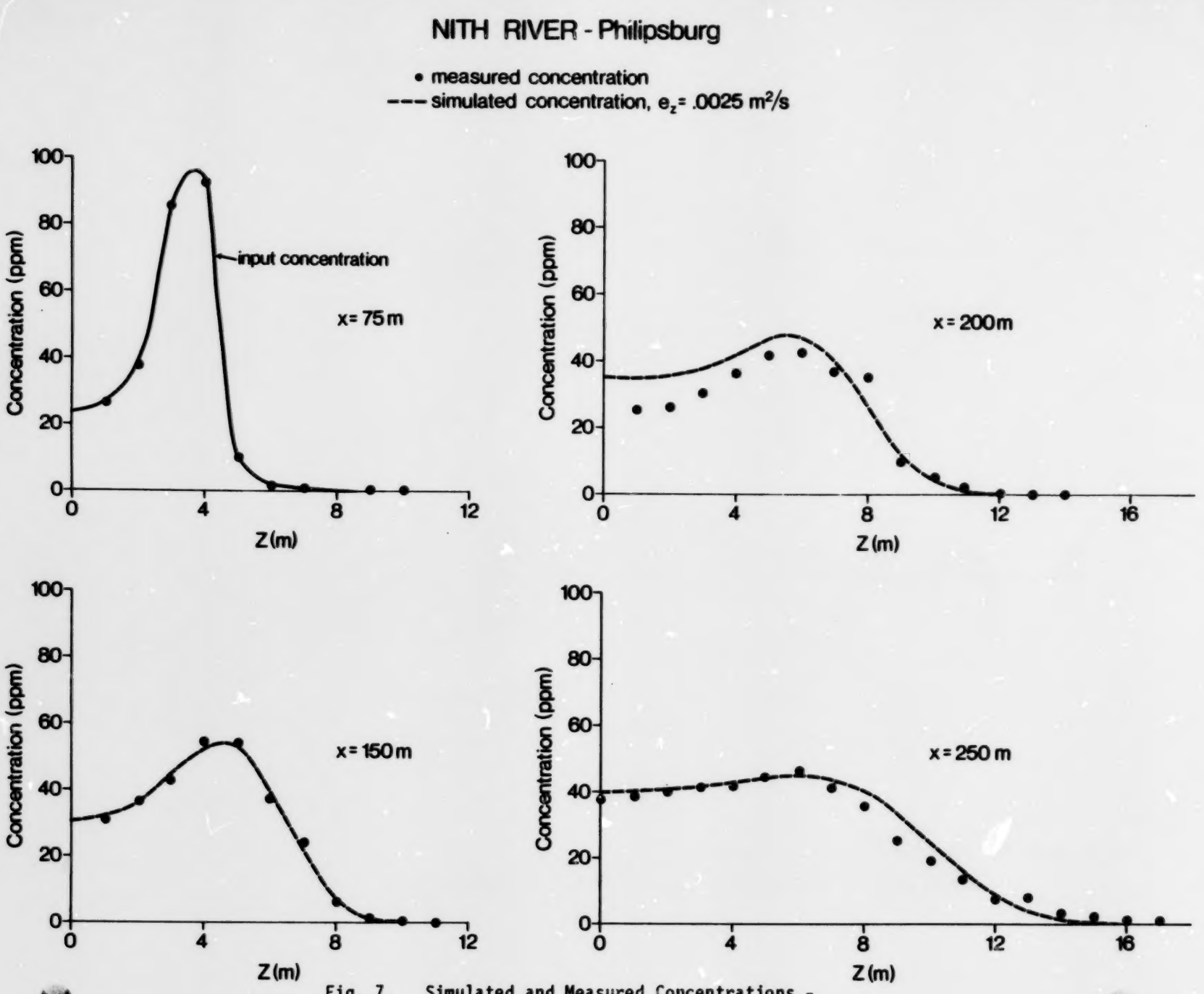

Fig. 7. Simulated and Measured Concentrations - Nith River at Philipsburg.

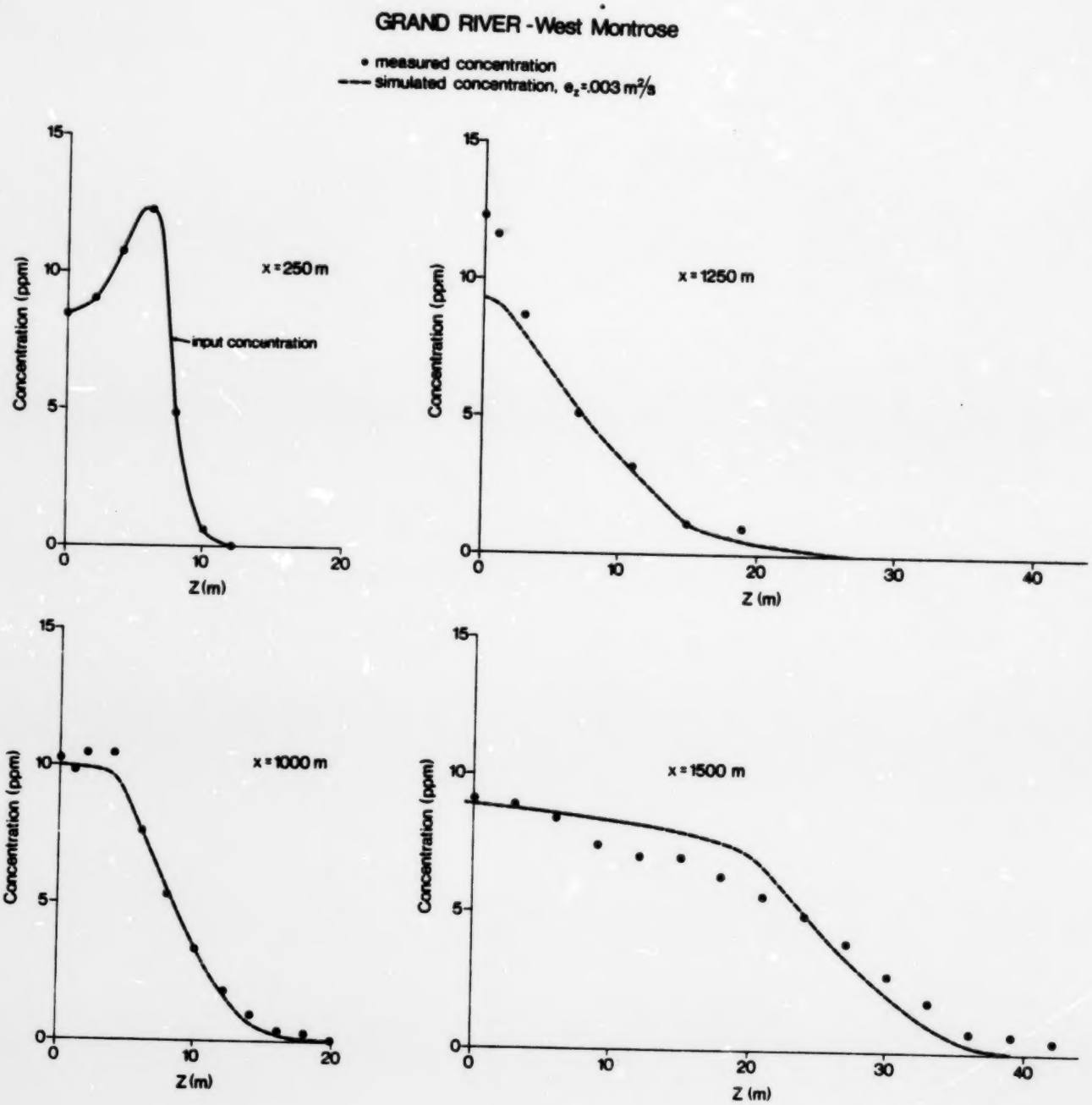

Fig. 8. Simulated and Measured Concentrations - Grand River near West Montrose.

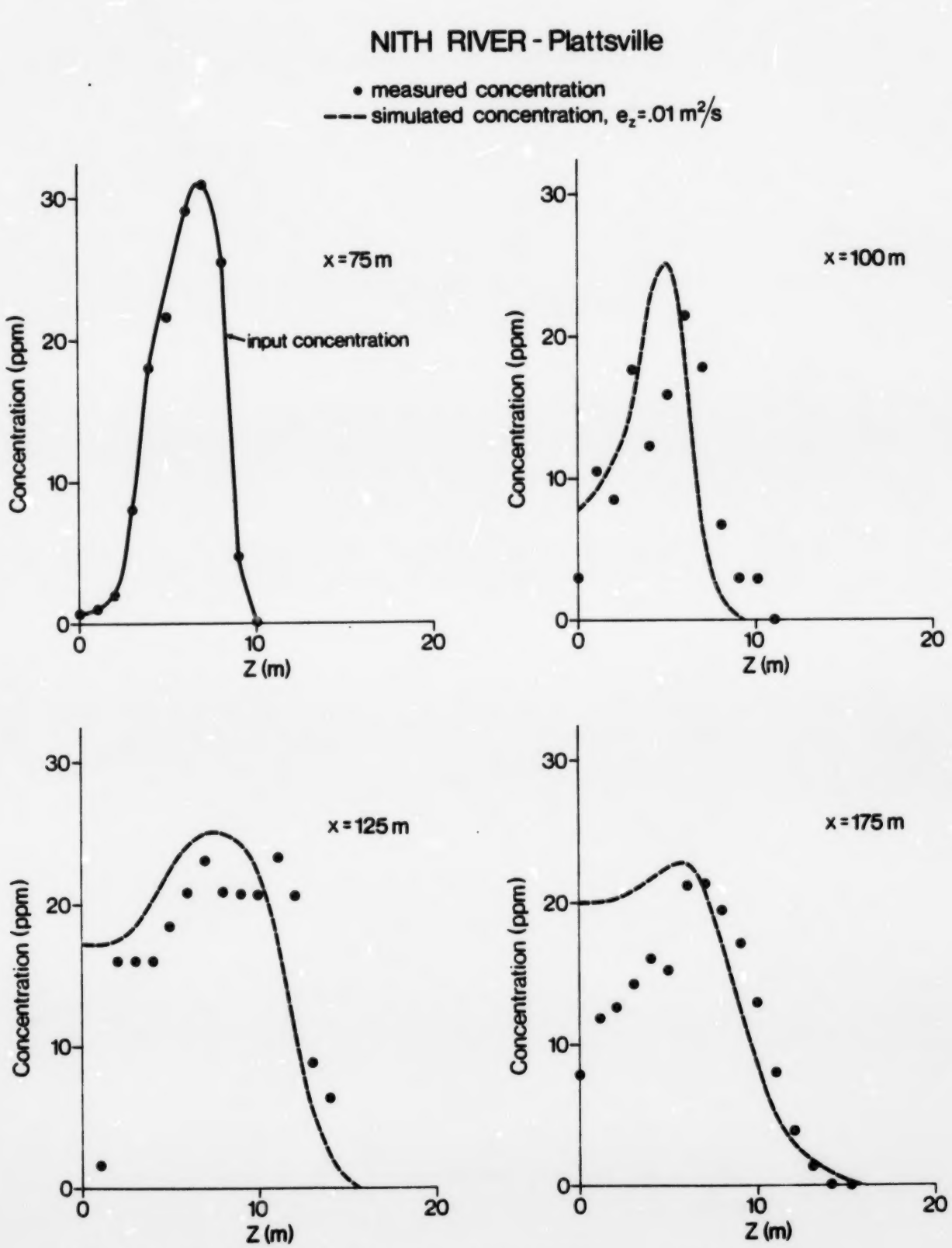

Fig. 9. Simulated and Measured Concentrations - Nith River near Plattsville.